The Variable Star Population of the globular cluster B514 in the Andromeda Galaxy*

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ABSTRACT

A rich harvest of RR Lyrae stars has been identified for the first time in B514, a metal-poor ([Fe/H]$\sim -1.95 \pm 0.10$ dex) globular cluster of the Andromeda galaxy (M31), based on Hubble Space Telescope Wide Field Planetary Camera 2 and Advanced Camera for Surveys time-series observations. We have detected and derived periods for 89 RR Lyrae stars (82 fundamental-mode −RRab− and 7 first-overtone −RRc− pulsators, respectively) among 161 candidate variables identified in the cluster. The average period of the RR Lyrae variables ($\langle Pab \rangle =$ 0.58 days and $\langle Pc \rangle = 0.35$ days, for RRab and RRc pulsators, respectively) and the position in the period-amplitude diagram both suggest that B514 is likely an Oosterhoff type I cluster. This appears to be in disagreement with the general

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*Based on data collected with the Wide Field Planetary Camera 2 on board of the Hubble Space Telescope and ACS HST archive data.

behaviour of the metal-poor globular clusters in the Milky Way, which show instead Oosterhoff type II pulsation properties.

The average apparent magnitude of the RR Lyrae stars sets the mean level of the cluster horizontal branch at $\langle V(RR) \rangle = 25.18 \pm 0.02$ (σ=0.16 mag, on 81 stars). By adopting a reddening $E(B-V) = 0.07 \pm 0.02$ mag (Schlegel et al. 1998), the above metallicity and M_V=0.44±0.05 mag for the RR Lyrae variables of this metallicity (Clementini et al. 2003), we derive a distance modulus of $\mu_0 = 24.52 \pm 0.08$ mag, corresponding to a distance of about 800 ± 30 kpc, based on a value of M_V that sets μ_0(LMC)=18.52.

Subject headings: galaxies: individual (M31) —globular clusters: individual (B514) —stars: distances —stars: variables: other —techniques: photometric

1. Introduction

The Andromeda galaxy provides us with a unique opportunity to study the formation and evolution of a massive spiral galaxy other than the Milky Way (MW). Various authors (van den Bergh 2000, 2006) suggested that M31 originated as an early merger of two or more massive metal-rich progenitors, accounting for the galactic halo wide range in metallicity (Durrell, Harris, & Pritchet 2001) and age (Brown et al. 2003) compared to the MW. There is also an interesting suggestion by Kravtsov (2002) that the "young" second-parameter globular clusters in our Galaxy, as well as at least some of the MW dwarf spheroidal companions, were in fact accreted from M31 when Andromeda was forming its Population II stars.

The pulsation properties of the variable stars in the field and globular clusters (GCs) of M31 have the potential to provide essential insights on the galaxy formation and to trace the merging episodes that led to the early assembling of the galaxy. The RR Lyrae stars, in particular, belonging to the old stellar population (t > 10 Gyr), were eyewitnesses to the first epochs of star formation in M31. Their mean periods along with the metallicities of the parent clusters can be used to set the luminosity of the horizontal branch (HB), and hence can provide precious information on how the M31 halo formed and evolved, in comparison with their MW counterparts (see e.g. Catelan 2004, 2009).

In the MW the vast majority of GCs which contain significant numbers of RR Lyrae stars sharply divide into two very distinct classes, the Oosterhoff types I and II (Oosterhoff 1939; see Catelan 2009 for a recent review) according to the mean pulsation periods of their RR Lyrae variables. Oosterhoff type I (OoI) GCs have $\langle Pab \rangle \simeq 0.56$ days, Oosterhoff

type II clusters (OoII) have $\langle Pab \rangle \simeq 0.66$ days (Clement et al. 2001). This phenomenon is referred to as the Oosterhoff dichotomy. There is evidence that OoI and OoII clusters in the MW may have different kinematical and spatial distributions thus possibly resulting from different accretion or formation events in the halo. This is supported also by a difference in mean chemical abundance, OoII clusters being on average more metal-poor than OoI clusters, and possibly by a difference in age, metal-poor clusters being on average slightly older than the intermediate-metallicity ones (van den Bergh 1993; De Angeli et al. 2005; Marin-Franch et al. 2009). Whatever the mechanism, it is clear that the Oosterhoff dichotomy reflects conditions within the MW halo at the time of GC formation. The existence or absence of the Oosterhoff phenomenon among the M31 GCs therefore provides information on the halo formation processes and thus on the chemical/dynamical evolution history of the dominant galaxy of the Local Group (Catelan 2004, 2009). Detection and characterization of RR Lyrae stars in M31 globular clusters is challenging since they are too crowded to be well-studied with ground-based telescopes. There has been only one previous attempt at detecting RR Lyrae stars in the globular clusters of M31. Clementini et al. (2001) used archival data obtained with the Wide Field Planetary Camera 2 (WFPC2) onboard the Hubble Space Telescope (HST) to make the first tentative detection of RR Lyrae stars in 4 clusters, namely, G11, G33, G64, and G322. A number of RR Lyrae candidates were identified in each cluster (two, four, eleven, and eight variables, in G11, G33, G64, and G322, respectively), but the small number of available data points and the short time baseline did not allow a definition of light curves and hence periods. As part of a Cycle 15 HST program we have observed a number of M31 GCs to properly characterize their variable star population. The clusters were selected as to have metallicities that, in the Milky Way, would place them either in the OoI or in the OoII groups. Here we present results for B514, a globular cluster located at a projected distance of ~ 55 Kpc from the M31 center, not far from the galaxy's major axis (Galleti et al. 2005). The color-magnitude diagram (CMD) indicates that B514 is a classical, old metal-poor globular cluster. The metallicity [Fe/H] is estimated as the weighted mean value of a few independent determinations, namely –1.8±0.3 (spectroscopic from Galleti et al. 2005), –1.8±0.15 (from the CMD, Galleti et al. 2006), and –2.14±0.15 (from the CMD, Mackey et al. 2007). The integrated absolute magnitude M_V has been estimated of ~ -9.1 mag, and classifies the cluster among the brightest globulars of M31. Moreover, the observed half-light radius $r = 1.6$ arcsec, corresponding to ~ 6 pc at the distance of M31 (see below), is significantly larger than for most clusters of the same luminosity (Federici et al. 2007).

In this Letter we present results of a search for variable stars which lead us to the discovery of about a hundred RR Lyrae stars in B514. This number is larger than found in the vast majority of the MW globular clusters, and since we are not able to resolving the

cluster's core, there are likely many more RR Lyrae stars in B514. This is the first time that a large sample of RR Lyrae stars is discovered in an M31 globular cluster and that their pulsation properties (periods, amplitudes, etc.) are fully characterized thus allowing to establish the cluster's Oosterhoff type. Here we focus on the Oosterhoff classification of B514 and on its importance to get hints on the formation of the Andromeda galaxy by comparison with the properties of variables in the MW globular clusters. We also present a $V, V-I$ CMD of B514 based on the ACS data extending to $V = 28$ mag. This is about half a magnitude fainter than the cluster CMDs by Galleti et al. (2006) and Mackey et al. (2007). The complete list of the cluster variables with ephemerides, photometric data and light curves, will be presented in Contreras et al. (2009, in preparation), where we will discuss in more detail their specific pulsation and evolutionary properties.

2. Observations and Data Reduction

Time-series F606W, F814W observations of B514 (R.A.= $00^h\ 31^m\ 09^s.83$, decl.= $37^\circ\ 53'\ 59''.6$) were obtained with the WFPC2 under HST program GO 11081 (PI G. Clementini) in June 12-14, 2007. The time series consisted of fifteen individual exposures in each filter, of 1100^s length, taken by alternating the filters. They were scheduled in three 10-orbit blocks executed almost continuously from 2007, June 12, UT $18^h\ 16^m\ 19^s$, to 2007, June 14, UT $01^h\ 23^m\ 38^s$, for total exposure times of 4 hours and 35 min in each band. The WFPC2 proprietary data were combined with ACS/WFC archive data from program GO 10394 (PI N.R. Tanvir), covering the period 2005, July 19-20, and from program GO 10565 (PI S. Galleti) obtained in 2006, June 10, making a total of 20 phase-points in the F606W-band and 21 phase-points in the F814W-band. Photometric reduction of the individual pre-reduced images supplied by the STScI pipeline was performed using HSTPHOT and Dolphot/ACSPHOT (Dolphin 2000a,b). These are PSF-fitting photometry packages specifically designed to perform photometry on point sources observed with HST/WFPC2 and HST/ACS. The packages identify sources above a fixed flux threshold and perform photometry on individual frames, taking into account information on CCD defects that are attached to the pre-reduced frames and automatically applying the correction for charge transfer efficiency (CTE) (Dolphin 2000a). Position, flight system magnitudes and Johnson-Cousins standard magnitudes of the sources are provided as output, along with a number of quality parameters of the measured sources (see Dolphin 2000a, for details). Typical errors of the combined photometry (8 ACS frames) for non-variable stars at the magnitude level of the B514 horizontal branch (HB, $V \sim 25.2$ mag) are $\sigma_V = 0.017$ mag, $\sigma_I = 0.015$ mag for the ACS dataset, and $\sigma_V = 0.019$ mag, $\sigma_I = 0.032$ mag for the WFPC2 data.

3. Variable Stars

Variable star candidates were identified from the scatter diagrams of the F606W and F814W datasets, using VARFIND, custom software developed at the Bologna Observatory by P. Montegriffo. We first analyzed the WFPC2 proprietary data, whose extended time series are optimized for the detection of variables of RR Lyrae type. The WFPC2 candidate variables were then counteridentified on the ACS data. A further search with VARFIND was later performed on the ACS archive data, and the counteridentification with the WFPC2 data was iteratively repeated. The search procedure returned a final catalogue of 161 candidate variables, most of which are located on the cluster HB. Many more will likely exist in the core of the cluster, that we have not detected. Periods and classification in type of the candidate variables were derived from the study of the light curves with Graphical Analyzer of Time Series (GRaTiS; see Clementini et al. 2000). We obtained reliable periods and light curves for 89 RR Lyrae stars: 82 fundamental-mode (RRab) and 7 first-overtone (RRc) pulsators. For the remaining 72 candidates we still lack a firm classification, mostly because of scatter in the data. The time sampling of our data covers nearly 29 hours in three observing blocks of 7 hours each, separated by two gaps of 50 minutes and 7 hours respectively. In addition, we have 6 epochs of archive data spaced by 694 and 368 days. This ensures that all possible periods of RR Lyrae stars are well sampled and no bias or alias effects are present, and allows us to derive accurate periods mostly to the 4th decimal digit.

Figure 1 shows the $V, V-I$ CMD of B514, obtained from the ACS data, for stars in four separate regions at increasing distance from the cluster center. Only sources with object type flag=1 (i.e. best measured stars), crowding <0.3, 0.5<sharpness<0.5, χ^2 <1.5 for V> 24 mag and χ^2 <2.5 for brighter stars are shown in the figure[1]. Confirmed variable stars are plotted as red filled circles, candidate variables with sufficient light curve sampling as blue filled circles, and less reliable candidates as green filled circles.

According to their position on the CMD, the vast majority of the candidate variables discovered in B514 are likely RR Lyrae stars. However, our candidate's list also includes a number of binaries and a few objects above and below the HB. Variable stars are plotted in the CMD using mean magnitudes and colors computed as simple averages of the available photometric measurements. The scatter observed around the average level of the HB is therefore largely due to variable stars with uneven coverage of the light curve, and will likely be significantly reduced when the mean magnitudes will be derived averaging over the full pulsation cycle. The upper panel of Figure 2 shows the location of the B514 variable stars on the $3' \, 22'' \times 3' \, 22''$ field of view covered by the ACS observations of Galleti et al. (2006).

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[1]The photometric data generating the CMD are available in electronic form upon request.

The lower panel of Figure 2 shows an enlargement of the variable stars' map corresponding to a $30'' \times 30''$ region around the cluster center. As noted in Federici et al. (2007), B514 is rather extended (see their Fig. 6) and its tidal radius was estimated as ~ 17 arcsec (~ 65 pc) from the analysis of the distribution of the integrated light and star counts. However, we have detected variables well beyond this distance, in particular five RR Lyrae stars are located farther than 50 arcsec and as far as ~ 90 arcsec from the cluster centre (Fig. 2). Although they are likely field stars, the CMD shown in Fig. 1 indicates that a non negligible fraction of the cluster population is still present in the annulus 50-100 arcsec, suggesting the possibility that at least a few of these distant variables may belong to the cluster. Radial velocity membership will be the most reliable way to assess to which population they belong.

Examples of light curves for 2 fundamental-mode and 2 first-overtone RR Lyrae stars we have identified in B514 are shown in Figure 3. The mean periods of the 89 confirmed RR Lyrae stars in B514 are $\langle Pab \rangle \sim 0.58$ days and $\langle Pc \rangle \sim 0.35$ days for fundamental mode and first-overtone variables, respectively, suggesting a possible dominance of Oosterhoff type I. Figure 4 shows the V-band period-amplitude diagram of the B514 RR Lyrae stars along with the Oosterhoff loci defined by the Galactic globular clusters from Clement & Rowe (2000) (linear relations), and the period-amplitude distributions of *bona fide* regular and evolved RRab stars in M3 (quadratic relations), from Cacciari et al. (2005).

The B514 RR Lyrae stars are close to the loci of Oosterhoff type I systems and regular RRab stars in M3. In conclusion, B514 appears to be a somewhat borderline OoI cluster, as it seems to follow a different rule than what is found in the MW where metal-poor ([Fe/H]$\lesssim -1.7$) GCs containing RR Lyrae stars show Oosterhoff type II properties. However, these results should be taken with caution since B514 could be a peculiar cluster. The entire sample of M31 clusters observed in our Cycle 15 program needs to be carefully analyzed (see Contreras et al. 2010, in preparation) to reach more firm conclusions on the Oosterhoff properties of the M31 globular clusters.

4. CMD and Distance

The CMD of B514 (see Figure 1) reaches $V \sim 28$ mag and is very rich in stars. It has well-populated horizontal and red giant branches. The HB stretches across the RR Lyrae instability strip, which is entirely filled by the large number of confirmed and candidate RR Lyrae stars, and extends significantly to the blue through a blue tail that reaches $V \sim 27$ mag at $B-V \sim 0.1$ mag. The red giant branch (RGB) is a prominent feature of the CMD, and does not exhibit significant scatter, thus ruling out a metallicity spread in B514.

The mean magnitude of the B514 RR Lyrae stars is $\langle V \rangle = 25.18 \pm 0.02$ mag (with a dispersion of 0.16 mag among the 81 stars). We adopt an absolute magnitude of $M_V = 0.44 \pm 0.05$ mag for RR Lyrae stars with the metallicity $[Fe/H] = -1.95 \pm 0.1$ dex of B514 (Clementini et al. 2003), which is consistent with an LMC distance modulus of 18.52. Using the reddening value of $E(B-V)$=0.07±0.02 estimated from Schlegel et al. (1998), we find a distance modulus of $\mu_0 = 24.52 \pm 0.08$ mag, which corresponds to a distance of about 800 ± 30 kpc, in good agreement with the distance adopted for this cluster by Galleti et al. (2006).

5. Conclusions

We have identified and obtained periods and light curves for 82 RRab stars and 7 RRc stars in the globular cluster B514 of the Andromeda galaxy. The average period of the B514 RRab stars for which we have complete and reliable light curves and their location on the period-amplitude diagram indicate likely OoI-type characteristics (see right side of Fig. 4), however the cluster's low metallicity is more typical of an OoII-type. Thus B514 seems to follow a different rule than what is found in the MW, where metal-poor ([Fe/H]$\lesssim -1.7$) GCs containing RR Lyrae stars have Oosterhoff II type. This may suggest that B514 is indeed a somewhat peculiar cluster, as indicated by independent evidence of some similarity with peculiar clusters in the MW such as ω Cen, M54 and NGC2419 (Federici et al. 2007). Alternatively, we are seeing an indication that the M31 GCs have different RR Lyrae pulsation characteristics than that seen in the main body of the MW GCs. A more detailed analysis will be done based on the entire sample of M31 clusters observed in our Cycle 15 program, and the results will be presented in a forthcoming paper (Contreras et al. 2010).

We warmly thank the Program Coordinator A. Roman, and the Contact Scientist M. Sirianni, of our HST program for their invaluable help with the Phase II and scheduling of the HST observations. This research was partially supported by COFIS ASI-INAF I/016/07/0. HAS and BP thank the Space Telescope Science Institute for support under grant HST-GO-11081.05-A. M.C. is supported by Proyecto Fondecyt Regular 1071002, by Proyecto Basal PFB-06/2007, by FONDAP Centro de Astrofísica 15010003, and by a John Simon Guggenheim Memorial Foundation Fellowship.

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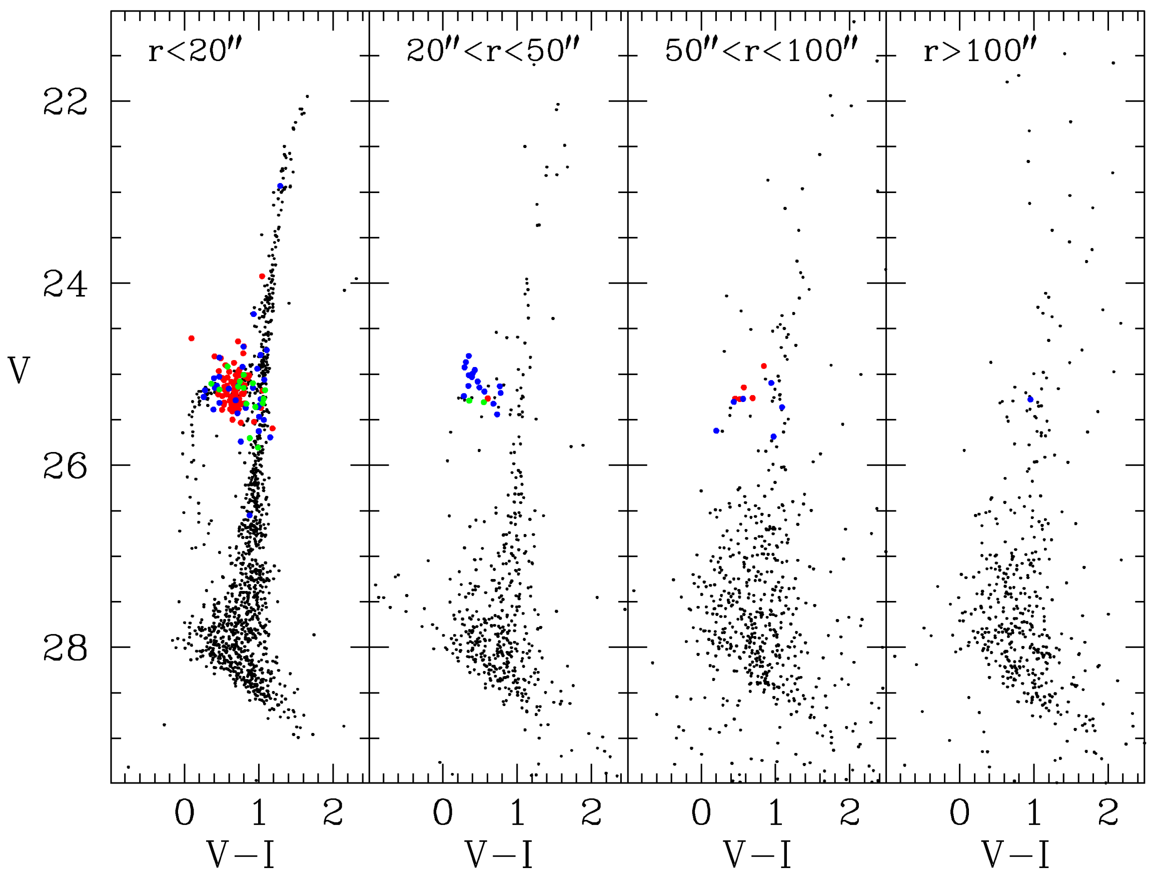
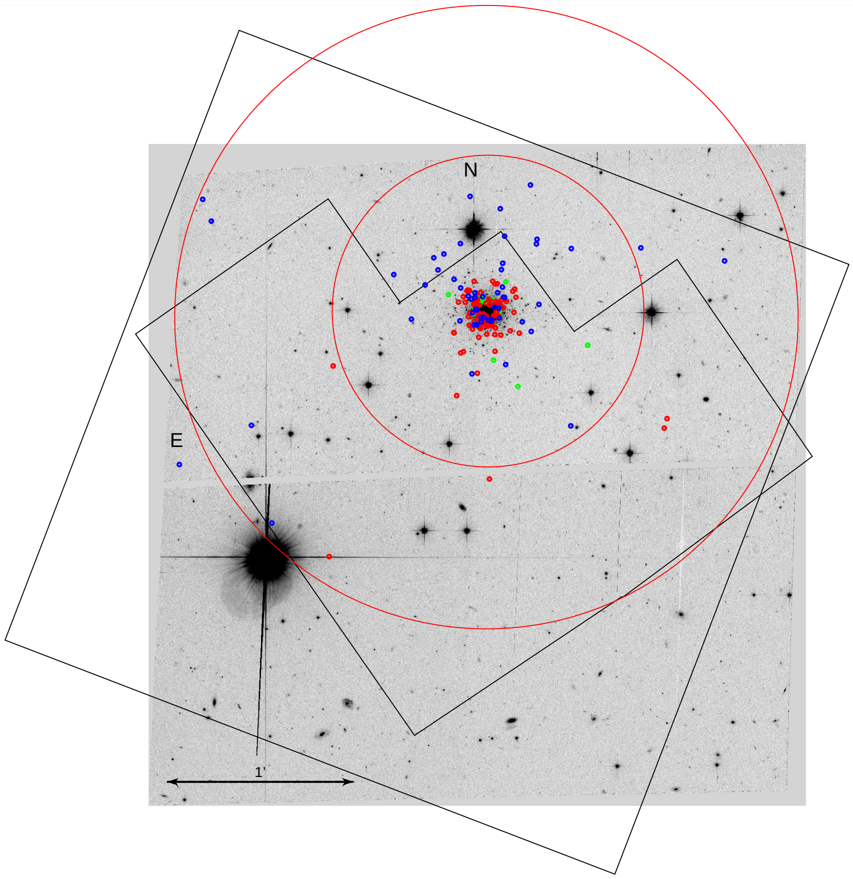


Fig. 1.— $V, V-I$ CMD of B514 in 4 regions with increasing the distance from the cluster center which was set at R.A.= 00^h 31^m $09^s.83$, decl.= $37°$ $53'$ $59''.6$ (J2000), based on our reductions of the ACS archive photometry. Bona-fide RR Lyrae stars are marked by filled red circles, candidate variable stars by blue and green filled circles (see Section 3).



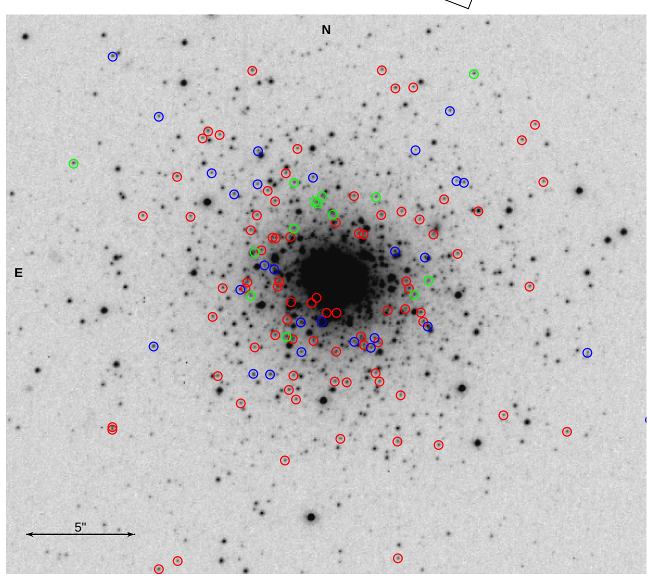


Fig. 2.— *Upper panel:* Location of B514 confirmed (red circles) and candidate (blue and green circles) variable stars on a $3' \, 22'' \times 3' \, 22''$ map of the cluster, corresponding to the field of view covered by the ACS observations of HST GO 10565 (see Galleti et al. 2006). Also shown are the field of view covered by the ACS observations of HST GO 10394 (see Mackey et al. 2007; tilted square), and the field of view of our WFPC2 observations. The two red circles correspond to radii of $r = 50''$ and $r = 100''$ from the center of B514. *Lower panel:* Enlargement of the variable stars' map showing a $30'' \times 30''$ region centered on the cluster.

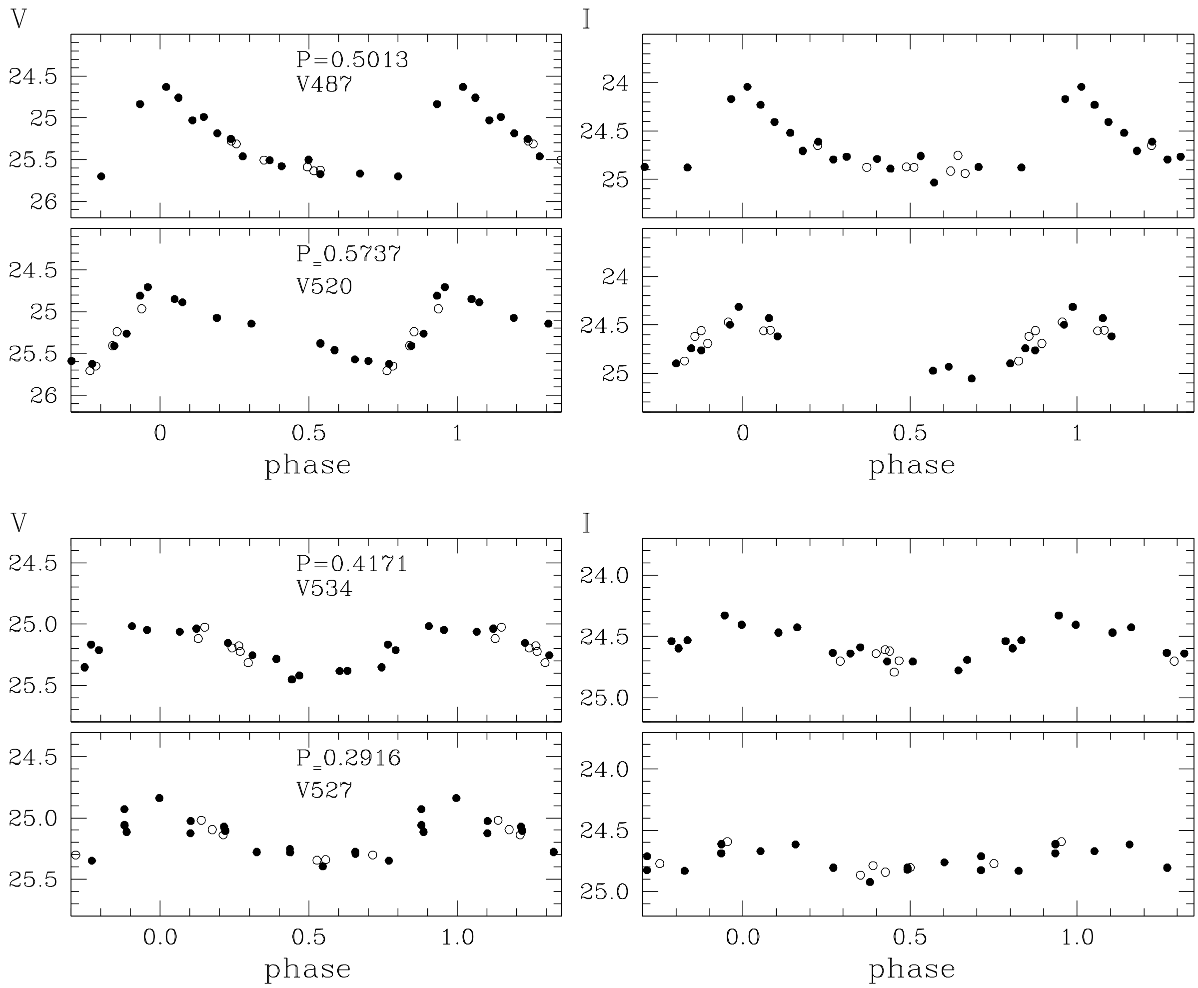


Fig. 3.— V (left panels) and I (right panels) light curves of RR Lyrae stars identified in B514. *Two upper rows:* fundamental-mode pulsators: *Two lower rows:* first-overtone pulsators. Filled and open circles indicate WFPC2 and ACS data, respectively. Typical error of the single data point at the magnitude level of the HB is about 0.06 mag.

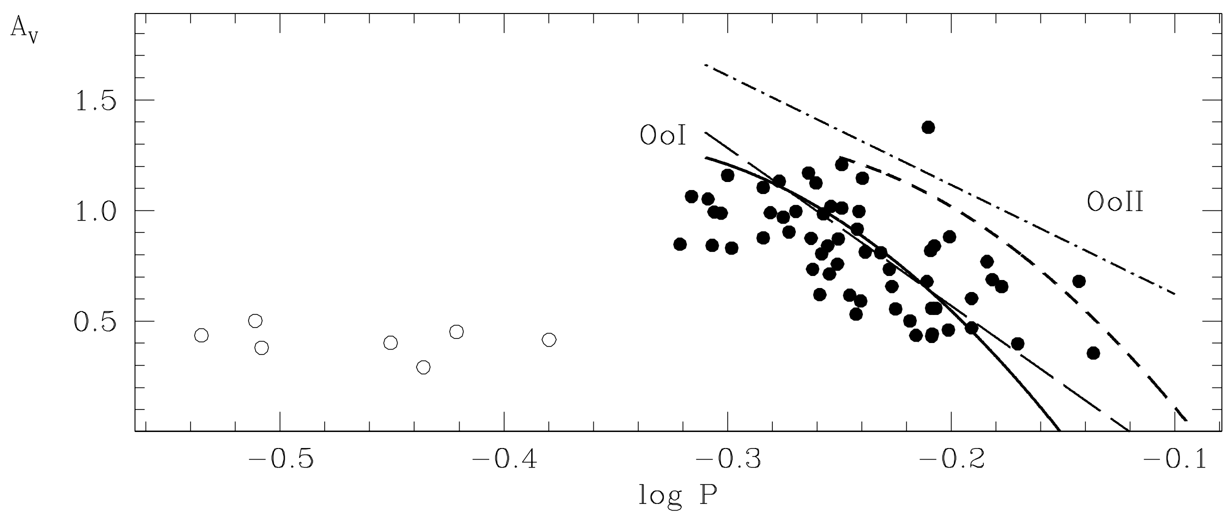


Fig. 4.— Period-amplitude diagram in the V band. RRab variables are shown by filled circles, RRc stars by open circles. The linear relations show the period-amplitude distributions of Galactic Oosterhoff type I and II clusters (Clement & Rowe 2000). The quadratic relations show the *bona fide* regular and evolved RRab stars in M3, from Cacciari et al. (2005), for comparison; analogous relations for the RRc stars are not reported because of the small number of these stars so far detected in B514.